AD-A102 525 NATIONAL MARITIME RESEARCH CENTER KINGS POINT NY COM--ETC F/G 13/10
AN INVESTIGATION INTO SAFETY OF PASSAGE OF LARGE TANKERS IN THE--ETC(U)
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UNCLASSIFIED CAORF-42-7703-015

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CAORF Technical Report
Research Study
42-7703-01S

AN INVESTIGATION INTO SAFETY OF PASSAGE OF LARGE TANKERS IN THE PUGET SOUND AREA

A Supplementary Study

W. McIlroy, Ph D

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May 1980

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Springfield, Virginia 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD

Office of Research and Development
Washington, D. C. 20590

LEGAL NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
	AD-A102525	

4. Title and Subtitle
An Investigation into Safety of Passage of Large Tankers in the Puget Sound Area - A Supplementary Study

5. Report Date
May 1980

6. Performing Organization Code

7. Author(s)
W. McIlroy, Ph D

8. Performing Organization Report No.
CAORF 42-7703-01S

9. Performing Organization Name and Address
National Maritime Research Center
Kings Point, New York 11024

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
MIPR Z 70099-8-843822

12. Sponsoring Agency Name and Address
U. S. Coast Guard
Office of Marine Environment and Systems
Washington, D. C. 20593

13. Type of Report and Period Covered
CAORF Technical Report
Research Study

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The first phase of the study was conducted in 1977 at the Computer Aided Operations Research Facility to investigate the safety of passage of tankers through the Puget Sound area under maximum credible adverse environmental conditions. The track-keeping results of that phase indicated that all ships were able to navigate safely under the extreme environmental conditions provided they maintained sufficient speed. The failed equipment runs indicated that tug support of ships was required to avoid grounding after suffering steering/propulsion failures. This supplementary study provides data on the transfer and advance of a 400K DWT tanker after a combined steering/propulsion failure under the same conditions as the earlier study. A formula relating tug force to ship tonnage was developed from data derived from the earlier study; computer runs in this study validated that formula. In addition, this supplementary study investigated the use of a rudder tug to control speed and heading of 120K, 165K, and 280K tankers.

Corrected sheets for the computational method presented in Volume I of the 1978 report are included.

17. Key Words
CAORF, oil tanker, Puget Sound, simulation, rudder tug, track keeping, tug boat assistance

18. Distribution Statement
Document is available to the U.S. public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
		35	

Form DOT F 1700.7 (8-72)

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LIST OF ABBREVIATIONS AND SYMBOLS

α	Angle of rudder tug to ship centerline
ψ	Actual heading
ψ_d	Desired heading
L	Ship length
F	Tug bollard force
U	Ship speed
DWT	Deadweight Tonnage
P-I-D	Proportional Integral Differential

1. INTRODUCTION

This study supplements the previous investigations reported in Volumes I and II of "An Investigation into Safety of Passage of Large Tankers in the Puget Sound Area," July 1978, performed at CAORF for the U.S. Coast Guard.

OBJECTIVES:

1) To provide data on the transfer and advance of a 400K DWT tanker after experiencing a combined steering and propulsion failure, under the same wind, current, and tug assistance conditions selected for the previous study.

2) To perform a series of specific computer runs to provide validation of a formula for the required tug force. The formula was developed from the previous study and incorporated into the regulations for tank vessel operations in the Puget Sound area (Federal Register, April 12, 1979).

3) To investigate the effectiveness of a tug attached at the stern ("rudder tug") which can be utilized to provide not only retarding or accelerating forces but also course-keeping control. Such a system has been investigated in a limited sea-trial at Port Valdez, Alaska, on July 25, 1978, with promising results. These results are reported in "A Preliminary Report of Exploratory Tanker - Tug Maneuvering Tests" prepared by the U.S. Coast Guard.

4) To correct editorial errors in Volume I of the 1978 Report concerning computations.

2. 400K DWT TANKER FAILURE STUDIES

The computer runs were made with ship speeds of 4, 6, 8, and 10 knots through the water and with wind and current conditions as shown in Table 1. Rudder failures occurred at -15° and at -35° (right rudder). Tugs (0, 2, or 4) were attached to the ship at all times on soft lines, and a 90-second delay was introduced between the time of the actual failure and the full application of tug force. When the ship speed through the water was greater than 6 knots, the tug force was further delayed until the ship had slowed to 6 knots. These constraints are identical to those used in the previous investigation.

The time, position, heading and ground speed listed in Table 2 were extracted from the computer data when the fore-and-aft speeds through the water had been reduced to 1 knot and 0.25 knot respectively. The 1-knot speed was selected because it corresponds to the point where, in the real world, tugs could begin attempting to turn the tanker and even disengage and hook up differently in an attempt to tow the ship to safety.

Table 2 shows the maximum values of advance and transfer under all the rudder failure/tug/environmental combinations for the 400K DWT tanker. Examination

TABLE I. 400K DWT TANKER CAORF RUNS

Current	Wind	Ship Speed	Tugs*	Rudder
-6 kt	$270^{\circ}/40$ 0 $90^{\circ}/40$	10 kt	0 2 4	15° 35°
0 kt	$270^{\circ}/40$ 0 $90^{\circ}/40$	8 kt 6 kt 4 kt	0 2 4	15° 35°
6 kt	$270^{\circ}/40$ 0 $90^{\circ}/40$	8 kt 6 kt 4 kt	0 2 4	15° 35°

* Each tug provides an 80,000-lb effective pulling force.

of this table shows trends consistent with the previous studies for the 80K, 120K, 165K, and 280K DWT ships, with the values for the 400K DWT ship lying within the same bounds.

In the absence of wind, the largest transfers occur for the smaller rudder angle failure. The transfer increases when the wind blows from the west (270°), and decreases with wind from the east (90°), as would be expected. The transfers are decreased when tugs are applied. However, the interaction is somewhat complex as the transfer depends upon the rudder failure angle, the wind direction and, what is most important, the ship speed, which governs the displacement that has occurred by the time the tugs first become effective (the time lag).

3. FORMULA VALIDATION

Based upon the previous CAORF data, the U.S. Coast Guard developed an empirical relationship for the tug force necessary to provide a maximum permissible value of the transfer distance.

$$F = KDU^2$$

where
- F = Static tug force in pounds
- D = Displacement tonnage (long tons)
- U = Ship speed through water in knots

and
- K = 47.433/maximum permissible transfer (in feet)

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE

No. of Tugs	Time to Slow to 1 Knot (min)	Ship Parameters When Speed Is 1 Knot X (ft)	1 Knot Y (ft)	1 Knot ψ (deg)	1 Knot Ground Speed (kts)	0.25 Knot X (ft)	0.25 Knot Y (ft)	0.25 Knot ψ (deg)	0.25 Knot Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 10 Knots / 6-Knot Head-on Current													
0	26:40	38833	55307	152.46	6.803	--	--	--	--	1,153	(5,594)	-15	0/0
2	14:20	47160	52771	105.36	5.704	44997	53076	111.48	5.672	1,155	3,076'	-15	0/0
4	11:10	48756	51980	91.08	5.257	47692	52114	94.74	5.407	1,155	2,114	-15	0/0
0	20:00	42250	53609	135.15	6.415	--	--	--	--	792	(4,445)	-35	0/0
2	10:50	47835	51799	97.57	5.446	45857	52065	104.32	5.575	792	2,065'	-35	0/0
4	8:30	48988	51255	85.32	5.029	47946	51380	89.71	5.320	792	1,380'	-35	0/0
0	13:30	47341	52444	99.58	5.563	45177	52729	105.90	5.669	1,040	2,729'	-15	40/90
2	10:30	48861	51693	85.70	5.076	47727	51830	89.28	5.330	1,040	1,830'	-15	40/90
4	9:10	49440	51334	78.62	4.828	48735	51398	81.01	5.161	1,040	1,398'	-15	40/90
0	10:40	47912	51653	94.10	5.337	45961	51903	100.53	5.552	757	1,903'	-35	40/90
2	8:30	48948	51145	82.75	4.933	47984	51246	86.32	5.244	757	1,246'	-35	40/90
4	7:20	49439	50879	76.17	4.692	48792	50931	78.89	5.084	756	931'	-35	40/90
0	27:00	38344	56263	179.32	7.057	--	--	--	--	1,316	(6,518)	-15	40/270
2	18:50	44759	54278	134.36	6.223	41943	54765	146.48	5.856	1,316	4,765'	-15	40/270
4	14:20	47561	52957	107.71	5.629	46000	53200	114.81	5.515	1,316	3,200'	-15	40/270
0	22:30	40161	54802	168.63	6.887	--	--	--	--	828	(4,802)	-35	40/270
2	14:50	45657	52912	122.59	5.960	42627	53428	137.56	5.749	828	3,428'	-35	40/270
4	10:40	48024	51856	97.89	5.393	46347	52097	105.80	5.453	828	2,097'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 8 Knots / No Current													
0	30:00	55196	55027	146.64	1.101	--	--	--	--	5,691	(5,027)	-15	0/0
2	14:10	55521	51995	91.27	1.215	55716	52236	97.04	0.514	5,716'	2,236	-15	0/0
4	10:50	55066	51240	75.90	1.372	55248	51340	79.80	0.652	5,248'	1,340	-15	0/0
0	20:20	54461	53140	125.22	1.14	--	--	--	--	4,482	(4,014)	-35	0/0
2	10:40	54126	51280	85.71	1.31	54363	51501	92.48	0.563	4,363'	1,501	-35	0/0
4	8:20	53750	50793	73.25	1.42	53936	50873	77.45	0.724	3,936'	873	-35	0/0
0	13:20	55157	51728	86.47	1.263	55391	51966	92.30	0.522	5,391'	1,966	-15	40/90
2	10:20	54677	51040	72.38	1.371	54871	51115	75.43	0.718	4,871'	1,115	-15	40/90
4	8:40	54310	50711	64.32	1.523	54483	50743	66.92	0.853	4,483'	743	-15	40/90
0	10:30	54062	51164	82.98	1.333	54328	51377	89.45	0.580	4,328'	1,377'	-35	40/90
2	8:10	53657	50695	70.92	1.485	53875	50768	74.88	0.778	3,875'	768'	-35	40/90
4	7:00	53381	50472	64.13	1.569	53552	50495	67.09	0.915	3,552'	495'	-35	40/90
0	30:00	--	--	--	--	--	--	--	--	(6,529)	(6,390)	-15	40/270
2	22:30	56640	54072	126.67	1.274	56690	54652	142.50	0.706	6,690'	4,652'	-15	40/270
4	15:30	56378	52207	88.32	1.211	56567	52437	94.10	0.573	6,567'	2,437'	-15	40/270
0	26:10	53614	55035	174.94	1.352	--	--	--	--	4,540	(5,377)	-35	40/270
2	17:00	54668	52696	115.20	1.243	54817	53321	134.34	0.677	4,817'	3,321'	-35	40/270
4	11:00	54256	51356	83.46	1.251	54473	51560	89.25	0.526	4,473'	1,560'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 6 Knots / No Current													
0	29:50	55579	54136	128.90	1.098	--	--	--	--	5,684	(4,154)	-15	0/0
2	13:30	54738	50940	68.83	1.202	55003	51085	74.51	0.517	5,033'	1,085'	-15	0/0
4	9:50	53830	50321	50.20	1.321	54022	50334	54.01	0.649	4,002'	339	-15	0/0
0	20:10	54435	52455	110.73	1.136	--	--	--	--	4,457	(3,378)	-35	0/0
2	10:20	53577	50680	69.54	1.282	53857	50822	76.13	0.564	3,857'	822'	-35	0/0
4	7:50	53017	50285	55.71	1.393	53212	50307	59.93	0.711	3,212'	309	-35	0/0
0	13:00	54484	50998	71.41	1.283	54810	51159	76.14	0.596	4,810'	1,159'	-15	40/90
2	9:40	53692	50372	55.54	1.368	53908	50381	58.28	0.781	3,908'	388	-15	40/90
4	7:50	53146	50125	46.21	1.450	53306	50102	48.50	0.891	3,306'	125'	-15	40/90
0	10:20	53564	50670	70.04	1.353	53903	50815	75.95	0.635	3,903'	815'	-35	40/90
2	7:50	53001	50272	57.12	1.480	53237	50287	60.90	0.823	3,237'	293	-35	40/90
4	6:30	52628	50105	49.46	1.572	52806	50084	52.53	0.938	2,806'	106	-35	40/90
0	--	--	--	--	--	--	--	--	--	10,217	(5,175)	-15	40/270
2	17:50	56814	50433	334.25	1.334	57064	50552	331.44	0.769	7,064'	552'	-15	40/270
4	12:20	54665	50300	343.81	1.267	54796	50396	341.28	0.813	4,796'	396'	-15	40/270
0	29:10	53766	55097	173.91	1.356	--	--	--	--	4,655	(5,181)	-35	40/270
2	20:00	54676	52286	100.36	1.143	54952	53055	125.17	0.603	4,952'	3,055'	-35	40/270
4	10:40	53621	50638	59.81	1.146	53839	50769	60.77	0.324	3,839'	769'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 4 Knots / No Current													
0	29:20	55625	52759	103.66	1.098	--	--	--	--	(5,637)	(2,832)	-15	0/0
2	12:20	53396	50185	42.35	1.172	53693	50206	48.41	0.500	3,693'	213	-15	0/0
4	8:30	52391	49986	25.10	1.147	52544	49947	29.29	0.542	2,544'	-53'	-15	0/0
0	19:40	54113	51526	89.97	1.135	--	--	--	--	(4,409)	(2,441)	-35	0/0
2	9:40	52674	50172	48.71	1.236	52973	50209	55.37	0.547	2,973'	211	-35	0/0
4	7:00	52036	49999	35.06	1.303	52220	49966	39.77	0.646	2,220'	-34'	-35	0/0
0	11:40	53239	50289	53.38	1.327	53679	50334	58.01	0.663	3,679'	342	-15	40/90
2	8:00	52341	49980	38.98	1.410	52588	49921	42.36	0.815	2,588'	-79'	-15	40/90
4	6:20	51882	49915	31.69	1.403	52035	49848	34.38	0.884	2,035'	-152'	-15	40/90
0	9:40	52685	50188	53.94	1.362	53100	50225	59.76	0.697	3,100'	231	-35	40/90
2	7:00	52050	49978	41.76	1.431	52286	49927	45.66	0.841	2,286'	-74'	-35	40/90
4	5:40	51700	49926	35.08	1.454	51854	49864	38.20	0.925	1,854'	-136'	-35	40/90
0	16:20	54528	49594	311.88	1.263	55018	49582	309.73	0.625	5,018'	-441	-15	40/270
2	10:00	52868	50068	329.24	1.345	53124	50160	326.62	0.761	3,124'	160'	-15	40/270
4	7:20	52131	50111	337.26	1.346	52287	50198	334.77	0.813	2,287'	198'	-15	40/270
0	--	--	--	--	--	--	--	--	--	5,498	(4677)	-35	40/270
2	18:20	54159	51022	23.16	1.143	54324	51377	14.15	0.698	4,324'	1377'	-35	40/270
4	9:20	52444	50214	11.38	1.045	52564	50331	8.36	0.569	2,564'	331'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING
400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 4 Knots / 6-Knot Following Current													
0	29:10	73294	52667	101.87	6.304	--	--	--	--	(23,816)	(2756)	-15	0/0
2	12:00	60606	50166	41.02	7.183	63163	50188	47.43	6.483	13,163'	193	-15	0/0
4	8:20	57410	49985	24.37	7.159	58860	49942	29.01	6.401	8,860'	-58'	-15	0/0
0	19:20	65805	514[illegible]	88.38	6.626	--	--	--	--	(22,594)	(2397)	-35	0/0
2	9:30	58402	5016[illegible]	47.90	7.222	60803	50195	54.67	6.539	10,803'	198	-35	0/0
4	7:00	56274	4999[illegible]	34.85	7.269	57578	49962	39.34	6.575	7,578'	-38'	-35	0/0
0	11:10	59870	50205	50.04	7.300	62875	50226	54.49	6.637	12,875'	238	-15	40/90
2	7:50	57014	49952	36.88	7.356	552	49888	39.87	6.689	8,552'	-112'	-15	40/90
4	6:10	55559	49905	29.93	7.344	56563	49839	32.39	6.687	6,563'	-161'	-15	40/90
0	9:20	58242	50135	51.35	7.325	60948	50152	56.80	6.672	10,948'	162	-35	40/90
2	6:50	56127	49958	39.99	7.393	57554	49904	43.51	6.743	7,554'	-96'	-35	40/90
4	5:30	54978	49918	33.56	7.417	55966	49856	36.53	6.748	5,966'	-144'	-35	40/90
0	15:40	63843	49757	316.71	7.248	67320	49781	314.67	6.584	17,320'	-256'	-15	40/270
2	9:40	58619	50105	332.55	7.310	60403	50205	330.19	6.589	10,403'	+205'	-15	40/270
4	7:10	56413	50123	339.65	7.254	57536	50208	337.43	6.551	7,536'	208'	-15	40/270
0	--	--	--	--	--	--	--	--	--	(23,256)	(4837)	-35	40/270
2	16:20	63645	50852	25.65	6.732	66217	51183	17.48	6.085	16,217'	1,183'	-35	40/270
4	8:50	57672	50202	13.90	6.921	59090	50313	12.44	6.164	9,090'	313'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Ad- vance* (ft)	Max. Trans- fer* (ft)	Rudder Angle (deg)	Wind (knots/ deg)
Initial Speed Through Water: 6 Knots / 6-Knot Following Current													
0	30.00	73788	54113	128.78	5.810	--	--	--	--	(23,788)	(4,113)	-15	0/0
2	13.20	62786	50903	67.88	7.005	65172	51043	73.53	6.51	15,172'	1,043'	-15	0/0
4	9:50	59775	50309	49.83	7.262	61107	50318	53.42	6.63	11,107'	318'	-15	0/0
0	20:20	66769	52448	110.50	6.24	--	--	--	--	(22,600)	(3,360)	-35	0/0
2	10:20	59834	50667	69.19	7.10	62179	50800	75.55	6.54	12,179'	800'	-35	0/0
4	7:50	57759	50278	55.46	7.34	59077	50297	68.76	6.70	9,077'	297'	-35	0/0
0	12:40	62074	50899	69.17	7.11	64636	51039	63.95	6.58	14,636'	1,039'	-15	40/90
2	9:20	59258	50322	53.47	7.38	60744	50328	56.42	6.75	10,744'	337	-15	40/90
4	7:40	57731	50101	44.68	7.45	58727	50070	46.92	6.80	8,727'	101	-15	40/90
0	10:10	59670	50616	68.52	7.19	62100	50739	74.22	6.61	12,100'	739'	-35	40/90
2	7:40	57593	50242	55.74	7.45	59042	50253	59.46	6.79	9,042'	260	-35	40/90
4	6:30	56543	50089	48.69	7.50	57483	50066	51.34	6.87	7,483'	89	-35	40/90
0	30:00	(77835)		(55414)	(126.03)		(6.035)		--	(27,835)	(5,414)	-15	40/270
2	17:30	67169	50592	341.80	7.265	69068	50742	338.89	6.52	19,068'	742'	-15	40/270
4	12:00	61770	50327	348.68	7.13	62845	50429	346.2	6.46	12,854'	429'	-15	40/270
0	30:00	(71731)		(55311)	(179.26)		(5.02)	--	--	(21,731)	(5,311)	-35	40/270
2	23:20	68852	52663	100.30	6.29	--	--	--	--	23,010	3,286	-35	40/270
4	10:30	59913	50607	57.89	6.95	62089	50732	56.75	6.21	12,089'	732'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

		Ship Parameters When Speed Is											
		1 Knot				0.25 Knot							
No. of Tugs	Time to Slow to 1 Knot (min)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Ad-vance* (ft)	Max. Trans-fer* (ft)	Rudder Angle (deg)	Wind (knots/deg)
Initial Speed Through Water: 8 Knots / 6-Knot Following Current													
0	30:00	(73412)	(55010)	(145.93)	(5.47)	--	--	--	--	(23,412)	(5010)	-15	0/0
2	14:00	63990	51944	90.28	6.77	66456	52190	96.18	6.42	16,456'	2,190'	-15	0/0
4	10:50	61620	51213	75.37	7.13	62997	51305	79.04	6.65	12,997'	1,305'	-15	0/0
0	20:40	66996	53160	125.55	5.95	--	--	--	--	(22,400)	(4011)	-35	0/0
2	10:40	60591	51265	85.38	6.94	62991	51480	91.99	6.49	12,991'	1,480'	-35	0/0
4	8:20	58799	50783	72.99	7.25	60134	50860	77.08	6.71	10,134'	860'	-35	0/0
0	13:10	63090	51640	85.20	6.85	65530	51859	91.34	6.41	15,530'	1,859'	-15	40/90
2	10:10	60784	50977	71.01	7.21	62143	51046	74.13	6.71	12,143'	1.046'	-15	40/90
4	8:40	59529	50671	63.35	7.38	60479	50693	65.65	6.84	10,479'	693'	-15	40/90
0	10:20	60284	51108	81.89	7.02	62695	51310	88.65	6.49	12,695'	1,310'	-35	40/90
2	8:10	58584	50666	70.23	7.31	59899	50725	73.85	6.77	9,899'	725'	-35	40/90
4	7:00	57602	50449	63.47	7.46	58515	50465	66.13	6.90	8,515'	467	-35	40/90
0	(30:00)	73102	56522	182.60	4.69	--	--	--	--	(23,102)	(6,522)	-15	40/270
2	24:30	71440	54393	129.96	6.04	--	--	--	--	(24,776)	(4,943)'	-15	40/270
4	15:50	65932	52187	85.13	6.66	68355	52407	87.93	6.30	18,355	2,407'	-15	40/270
0	27:40	70083	55279	182.78	5.03	--	--	--	--	(21,275)	(5,471)	-35	40/270
2	18:30	65886	52913	117.66	6.24	70777	53628	139.54	6.23	20,777'	3,628'	-35	40/270
4	11:10	61015	51353	81.95	6.83	63388	51556	85.71	6.37	13,388'	1,556'	-35	40/270

* See notes on last page of table.

TABLE 2. EFFECTIVENESS OF TUGS IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE (CONT)

NOTES:

a. Ship's initial heading: 000° T

b. Computer coordinates of ownship at the time of rudder failure:

X_o = 50,000 ft

Y_o = 50,000 ft

c. Negative values of current denote head-on current (setting 180°).

d. Runs were terminated after the ship speed had been reduced to 0.25 knot or after 30 minutes, whichever occurred first. Values shown without a prime (') and without parentheses are those that had been reached before that run was terminated. Values shown primed were maximum values achieved at 0.25 knot; the run was terminated before actual maximum was reached. Values shown in parentheses were obtained in runs terminated at 30 minutes, before the ship speed had been reduced to 0.25 knot.

The displacement tonnage D = k x (DWT), where k = 1.19, 1.09, 1.14, and 1.16 for the 120K, 165K, 280K, and 400K DWT tankers, respectively.

The details of the derivation of this formula are presented in "Summary of Development of Tug Assistance Formula for Proposed Tanker Regulations for Puget Sound," prepared by U.S. Coast Guard.

The matrix of validation runs that were performed in this study is shown in Table 3. Four ship sizes are evaluated, all at 8-knot ship speed and in the absence of current. Wind is either absent, or blows from the east or west as previously, at 40 knots. The calculations were carried out using dynamic retarding forces rather than the static bollard pulls estimated from the above formula. The tanker-tug trials at Port Valdez indicated that the actual pulls experienced when the tug is thrusting against the motion of the ship are larger than the static pull calculated under the same engine conditions. An effective multiplying factor of 1.20 was therefore recommended by the U.S. Coast Guard in calculating the dynamic tug forces to be applied in this study.

The results of these computer runs are shown in Tables 4 through 7. From the data, it can be seen that the actual transfer for the 165K DWT was well within the acceptable values. The transfer for the 120K and 280K DWT ships slightly exceeded the maximum permissible value of 3,760 feet -- the 120K DWT exceeded its maximum permissible value by 227 feet when the rudder failed at -15° and the wind was from the west, while the 280K DWT exceeded its value by 156 feet with the wind also from the west but with the rudder failed at -35°.

TABLE 3. VALIDATION MATRIX

Ship Size	Current	Wind	Ship Speed	Rudder Position	K Factor	Maximum Permissible Transfer	Static* Tug Force	Dynamic** Tug Force
120K DWT	0	$40/270^{\circ}$ 0/0 $40/90^{\circ}$	8 kts	15° 35°	0.01262	3,760 ft	115,379 lbs	138,454 lbs
165K DWT	0	$40/270^{\circ}$ 0/0 $40/90^{\circ}$	8 kts	15° 35°	0.02118	2,240 ft	244,740 lbs	293,688 lbs
280K DWT	0	$40/270^{\circ}$ 0/0 $40/90^{\circ}$	8 kts	15° 35°	0.01262	3,760 ft	257,592 lbs	309,110 lbs
400K DWT	0	$40/270^{\circ}$ 0/0 $40/90^{\circ}$	8 kts	15° 35°	0.01262	3,760 ft	375,572 lbs	450,686 lbs

* Regulation Static Requirement.

** Effective Tug force generated - value to be used in CAORF runs.

TABLE 4. EFFECTIVENESS OF 138,454-LB TUG FORCE IN SLOWING 120K DWT TANKER AFTER RUDDER FAILURE, NO CURRENT

Time to Slow to 1 Knot (min)	Ship Parameters When Speed Is 1 Knot: X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	0.25 Knot: X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/(deg)
10:20	54120	52071	93.93	1.15	54188	52167	97.62	0.54	4,188'	2,167'	-15	0/0
7:20	52783	51385	93.06	1.26	52869	51487	97.42	0.62	2,869'	1,487'	-35	0/0
7:40	53483	51157	74.27	1.38	53597	51206	76.83	0.79	3,597'	1,206'	-15	40/90
6:00	52610	50864	76.60	1.42	52720	50912	79.52	0.85	2,720'	912'	-35	40/90
16:10	55919	53815	110.17	1.20	55976	53987	117.68	0.65	5,976'	3,987'	-15	40/270
9:20	52945	52101	112.61	1.22	53013	52257	119.15	0.73	3,013'	2,257'	-35	40/270

* Values of advance and transfer shown primed are those obtained at speed of 0.25 knot which was when the run was terminated.

TABLE 5. EFFECTIVENESS OF 293,688-LB TUG FORCE IN SLOWING 165K DWT TANKER AFTER RUDDER FAILURE, NO CURRENT

Time to Slow to 1 Knot (min)	Ship Parameters When Speed Is 1 Knot X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	0.25 Knot X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/(deg)
9:40	54699	51713	77.26	1.20	54763	51760	80.01	0.58	4,763'	1,760'	-15	0/0
7:10	53249	51262	79.58	1.26	53318	51310	82.45	0.65	3,318'	1,310'	-35	0/0
7:20	53636	51038	68.36	1.28	53702	51055	70.20	0.83	3,702'	1,055'	-15	40/90
6:00	52878	50832	69.63	1.37	52954	50854	71.86	0.87	2,954'	854'	-35	40/90
12:50	57345	49867	326.91	1.27	57418	49891	325.01	0.82	7,418'	-136	-15	40/270
9:00	53821	51853	87.12	1.18	53881	51928	90.53	0.51	3,881'	1,928'	-35	40/270

* Values of advance and transfer shown primed are those obtained at speed of 0.25 knot which was when the run was terminated.

TABLE 6. EFFECTIVENESS OF 309,110-LB TUG FORCE IN SLOWING 280K DWT TANKER AFTER RUDDER FAILURE, NO CURRENT

Time to Slow to 1 Knot (min)	Ship Parameters When Speed Is: 1 Knot				0.25 Knot							
	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/(deg)
16:20	57096	53330	69.06	1.03	57149	53418	72.70	0.28	7,149'	3,418'	-15	0/0
12:30	54766	52653	84.82	1.06	54802	52754	90.21	0.30	4,802'	2,754'	-35	0/0
11:10	55254	51817	66.35	1.142	55331	51859	69.69	0.556	5,331'	1,859'	-15	40/90
9:10	54035	51538	72.05	1.146	54105	51588	76.02	0.530	4,105'	1,588'	-35	40/90
17:50	59093	51938	357.54	1.201	59188	52022	353.01	0.72	9,188'	2,022'	-15	40/270
17:20	56295	53786	51.53	1.032	56319	53926	44.62	0.48	6,322	3,926'	-35	40/270

* Values of advance and transfer shown primed are those obtained at speed of 0.25 knot which was when the run was terminated.

TABLE 7. EFFECTIVENESS OF 450,686-LB TUG FORCE IN SLOWING 400K DWT TANKER AFTER RUDDER FAILURE, NO CURRENT

Time to Slow to 1 Knot (min)	Ship Parameters When Speed Is 1 Knot X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	0.25 Knot X (ft)	Y (ft)	ψ (deg)	Ground Speed (kts)	Max. Advance* (ft)	Max. Transfer* (ft)	Rudder Angle (deg)	Wind (knots/(deg)
9:40	54817	50958	69.41	1.368	54935	51000	72.10	0.757	4,953'	1,000'	-15	0/0
7:20	53532	50594	67.28	1.489	53688	50631	70.60	0.822	3,688'	631'	-35	0/0
8:00	54117	50563	60.38	1.50	54245	50568	62.27	0.94	4,245'	572	-15	40/90
6:30	53231	50365	60.64	1.54	53354	50365	62.76	1.00	3,354'	370	-35	40/90
12:50	56014	51562	75.76	1.22	56165	51665	78.30	0.53	6,164'	1,665'	-15	40/270
9:00	53950	50936	73.25	1.30	54118	51025	76.36	0.59	4,118'	1,025'	-35	40/270

* Values of advance and transfer shown primed are those obtained at speed of 0.25 knot; run was terminated before maximum values were reached.

For the 400K DWT tanker, the calculated transfers were very much smaller than the maximum value of 3760 feet. The largest transfer (1,665 feet) for the 400K DWT tanker occurred when the rudder failed at -15^{o} and the wind was from the west.

4. RUDDER TUG CONTROL

Two forms of rudder tug control were studied. In one, the tug was pushing on the stern and pivoting so as to provide a turning moment on the ship. In the other, the tug at the stern was pulling against the ship's motion at an angle, thereby providing a decelerating force and a turning moment on the ship. (The previous study maintained this decelerating force in the fore-aft direction so that it did not provide a controlling moment on the ship.)

The rudder-tug was used in an attempt to bring the ship back on course following a combined rudder/engine failure. As in the previous study, a 90-second time lag was introduced. Due to the similarity between the action of a rudder and the action of tugs in controlling a ship, an "Autotug" equation similar to the conventional course-keeping P-I-D controller was developed as used to control the angle, α , between the tug line of action and the ship centerline, as shown in Figure 1.

Special note should be taken here of the limitations of this preliminary study of rudder-tug control. The first limitation results from the neglect of the presently unknown, complex hydrodynamic flows and forces acting on both the tug and the ship. A constant tug force acting at various angles was the only force included in the analysis. Two values were used: 80,000 and 160,000 pounds. It is probable that the hydrodynamic forces are substantial, probably additive (diminishing the transfer) in the rudder-tug pushing mode and possibly subtractive in the pulling mode. The second limitation is one of practicality. Most normal tugs can perform the rudder-tug angular pushing actions since the water flow over their rudders is substantial and basically from forward to aft in this mode. However, for the pulling mode, it is probable that only the highly maneuverable types could perform the angular pulls since the water surrounding the rudder for the normal type is in a highly confused state.

The Autotug equation used to determine the tug angle, α (positive when measured clockwise) is

$$\alpha = A(\psi - \psi_d) + B\left(\frac{L}{U}\right)\dot{\psi} + C\left(\frac{U}{L}\right)\int_0^t (\psi - \psi_d)\,dt$$

where U = Ship speed in feet/second

L = Ship length in feet

A, B, C are dimensionless gains = 4, 2, 0.5, respectively. (These values were found appropriate in other studies performed at CAORF.)

ψ = Ship heading (degrees)

ψ_d = Desired ship heading (initial heading at time of failure).

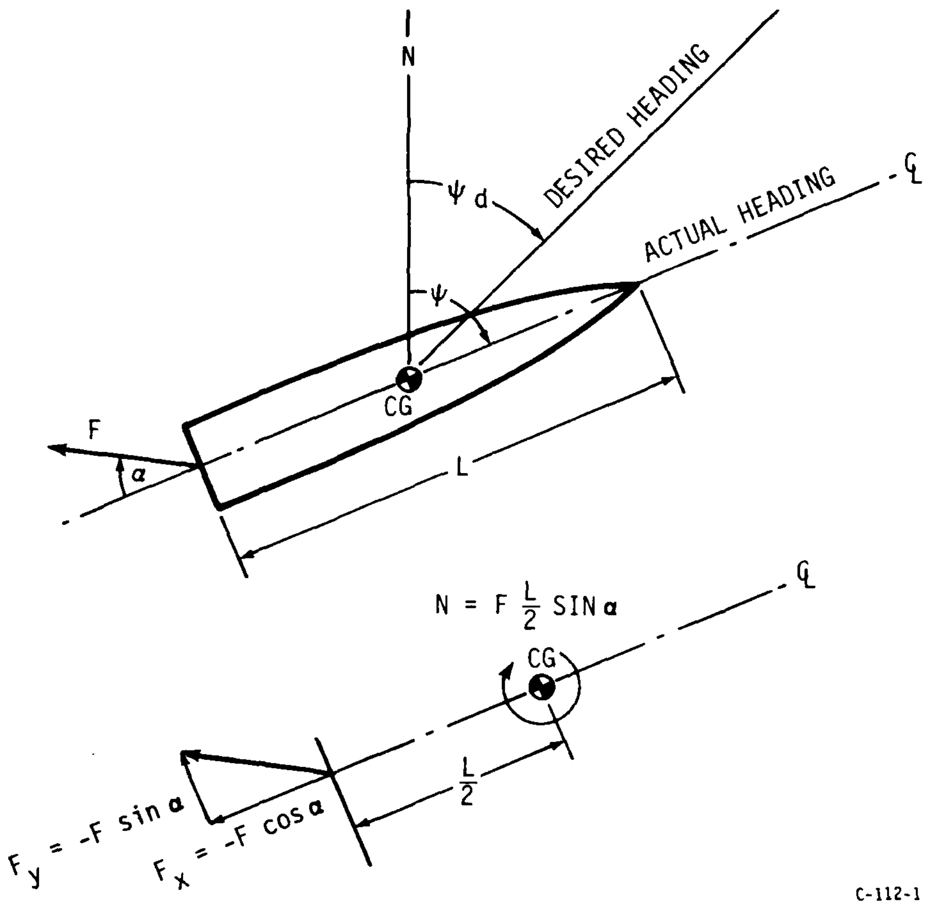


Figure 1. Notations Used in Autotug Equation

If F = tug force (positive when the tug is pulling on the stern, Figure 1).

then F_x = $-F \cos \alpha$ = longitudinal tug force

F_y = $-F \sin \alpha$ = lateral tug force

N = $F (L/2) \sin \alpha$ = moment about the ship c.g.

The rudder tug calculations were performed with the ship heading initially to the west (270°). In the case of the 80K DWT ship, winds were also included, blowing from the north onto the starboard beam and from south onto the port beam. Relative to the ship, these wind directions are similar to those used in previous studies.

Rudder Tug Pushing

Runs made with the 80K DWT ship are shown Table 8. The ship speed was 6 knots, rudder failures occurred at -15° and -35°, and currents were absent in all cases. Two levels of tug force were used, 80,000 and 160,000 with the tug

TABLE 8. RUDDER TUG IN PUSHING MODE (TUG ANGLE UNLIMITED)

Rudder Angle At Failure (deg)	Tug Force (lb)	Max Tug Angle (deg)	After 30 Minutes				
			Course	Speed (kts)	Transfer (ft)	Advance (ft)	Heading
Ship Type: 80K DWT, Speed at Failure = 6 knots, Course = 270^{o}							
No Wind							
-15	-80,000	69.59	266.64	6.15	1,063	18,342	263.70
-15	-160,000	69.98	264.84	9.40	864	25,690	265.47
-35	-80,000	Excessive (> 90^{o})	--	--	--	--	--
-35	-160,000	Excessive (> 90^{o})	--	--	--	--	--
Wind 40/0^{o} (Starboard Beam)							
-15	-160,000	68.77	271.30	7.63	920	21,771	271.10
-35	-160,000	Excessive (> 90^{o})	--	--	--	--	--
Wind 40/180^{o} (Port Beam)							
-15	-160,000	34.55	269.25	10.03	926	27,371	267.76
-35	-160,000	63.32	269.46	6.77	1,432	20,174	263.93

pushing on the stern and pivoting to provide course-keeping control. The tug angle was unrestricted in this case.

For the -15° rudder failure a maximum tug angle of approximately 70° was required, whereas an impractical value of much greater than 90° was needed when the -35° failure took place. Transfers are shown after a 30-minute period, along with the corresponding ship heading, course and speed. It can be seen that, with the larger tug force, a considerable increase in speed occurred up to 10 knots, at which level the tug effectiveness becomes questionable. Table 8 also presents similar results in the presence of beam winds from port and starboard.

For the remainder of the rudder tug runs, in both this pushing and also the retarding case, the tug angle was limited to a maximum value of 60°.

Table 9 presents data for comparing the behavior of the three ship types with ship speeds of 3 and 6 knots and under the control of rudder tugs.

From these data, when a -15° rudder failure occurs, it appears that the maximum transfer after 30 minutes increases with increasing ship size at speeds of 6 knots, but the opposite is true when the speed is 3 knots. The transfers for the 80K and 165K DWT tankers decrease considerably with increased tug force at 6-knot initial ship speeds, but are only slightly larger in the case of the 3-knot ship speed. When the rudder fails at the higher angle, high values of transfer result (8,100 to 9,400 feet) at the 6-knot speed when an 80,000 pound force is applied for all the ship sizes considered. For the 80K DWT tanker, the transfer is high (9,426 and 6,492 feet) with both levels of tug force, but there is a considerable reduction in the case of the other ships when the tug force is doubled.

At 3 knots and the 35° rudder failure, the 165K DWT ship has the highest transfer with the 80,000-pound tug force; the transfer is reduced when this force is doubled. The 80K DWT tanker, on the other hand, appears to develop a larger transfer with the larger tug force, whereas the transfer of the 280K DWT ship is not altered significantly.

From these observations, it is apparent that there are no obvious proportional changes in transfer magnitudes either with ship size or with tug pushing force. For given tug forces and ship speeds, however, the transfers are always higher when the rudder failure angle is higher. It must be emphasized, however, that these observations are based on transfers occurring after a period of 30 minutes. In many cases, higher transfers can occur either before 30 minutes have elapsed or afterwards. In Figure 2, comparisons of ground tracks for the three ships sizes are made as functions of rudder failure angle and ship speed. The total time period encompassed by each plot is 60 minutes, and the 30 minute points are indicated. From these plots, the maximum extent of the transfers can be readily seen.

Retarding Tug Control

In this case, the rudder tug not only provides a retarding force to slow the ship, but also provides a turning moment opposite to that caused by the rudder failure in an attempt to maintain the original course of 270°.

TABLE 9. RUDDER TUG IN PUSHING MODE
(TUG ANGLE LIMITED TO 60°)

Rudder Angle At Failure (deg)	Tug Force (lb)	Max Tug Angle (deg)	After 30 Minutes				
			Course	Speed (kts)	Transfer (ft)	Advance (ft)	Heading
Ship Speed = 3 Knots, Course = 270°, Wind = 0/0°							
Ship Type: 80K DWT							
-15	-80,000	48.78	270.47	6.64	830	16,822	270.26
-15	-160,000	56.32	270.17	9.47	882	23,908	270.41
-35	-80,000	60.00	267.07	4.34	1,767	12,444	262.26
-35	-160,000	60.00	312.07	6.31	4,076	16,806	311.61
Ship Type: 165K DWT							
-15	-80,000	60.00	268.47	5.56	759	13,706	267.14
-15	-160,000	60.00	271.86	8.17	869	19,131	271.36
-35	-80,000	60.00	314.95	3.93	2,263	10,970	320.16
-35	-160,000	60.00	285.76	6.06	1,523	15,775	289.04
Ship Type: 280K DWT							
-15	-80,000	36.6	273.00	4.17	691	11,077	272.94
-15	-160,000	37.0	272.48	5.96	732	14,470	272.44
-35	-80,000	45.4	274.10	3.38	1,003	9,671	274.12
-35	-160,000	45.4	273.50	4.78	1,040	12,639	273.49

TABLE 9. RUDDER TUG IN PUSHING MODE (TUG ANGLE LIMITED TO 60°) (CONT)

Rudder Angle At Failure (deg)	Tug Force (lb)	Max Tug Angle (deg)	After 30 Minutes				
			Course	Speed (kts)	Transfer (ft)	Advance (ft)	Heading
Ship Speed = 6 Knots, Course = 270°, Wind = 0/0							
Ship Type: 80K DWT							
-15	-80,000	60	273.04	6.01	1,210	18,282	269.50
-15	-160,000	60	262.60	9.28	889	25,554	263.06
-35	-80,000	60	276.55	3.18	9,426	6,486	263.15
-35	-160,000	60	306.04	6.11	6,492	15,633	301.50
Ship Type: 165K DWT							
-15	-80,000	60	260.32	4.16	1,865	14,024	269.62
-15	-160,000	60	283.84	6.41	873	20,449	290.21
-35	-80,000	60	028.80	3.61	8,469	293	022.01
-35	-160,000	60	270.45	3.95	1,146	9,057	256.43
Ship Type: 280 DWT							
-15	-80,000	60	264.75	4.33	2,404	14,649	263.94
-15	-160,000	41.68	271.16	6.27	1,153	18,370	271.12
-35	-80,000	60	332.16	3.42	8,109	8,699	331.61
-35	-160,000	60	267.93	4.85	1,888	14,617	268.44

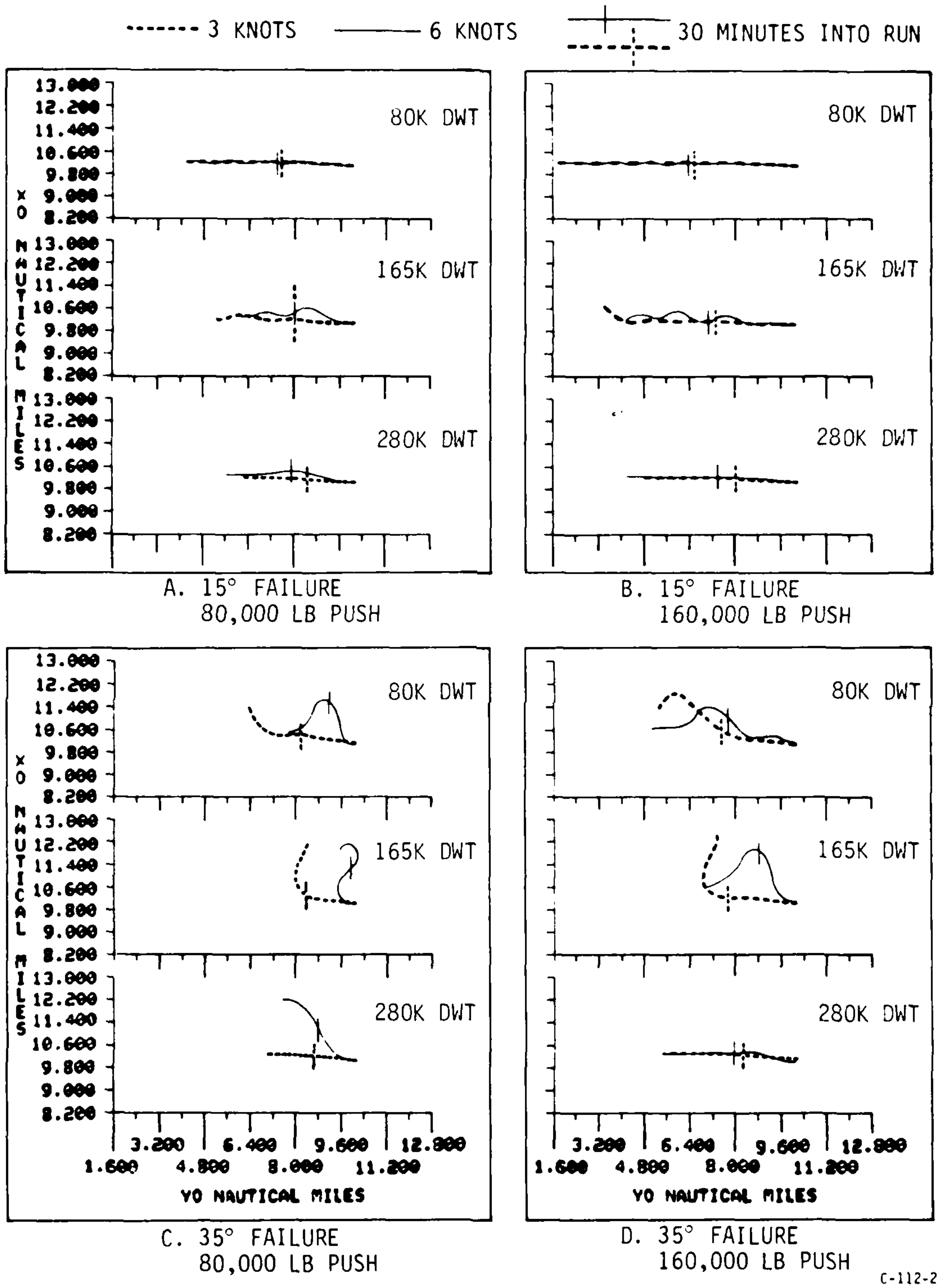


Figure 2. Effectiveness of Pushing Tugs on 80K, 165K, and 280K DWT Tankers with 15° and 35° Rudder Failure

In all computer runs, wind and current were set to zero, and the rudder-tug angle was limited to a maximum value of 60°. Whereas in the pushing case the tug applied a pushing force inclined at a positive angle to the ship's fore-and-aft axis (to port side), here the tug applied a pull at a negative angle to the ship centerline, on the starboard side. Three ship types were again studied, and the data are presented in Table 10, and the actual ship trajectories are shown in Figure 3 with a time period of two minutes between each ship position. Note that the X and Y axis scales are different from those in Figure 2. Again the tracks are shown when the failure rudder angles are -15° and -35°, and the speeds are 3 and 6 knots respectively. As seen in Table 10, the transfers, when the ship speed reaches 1 knot and also 0.25 knot levels, are much higher when the ship speed is higher, and also increase with increasing ship size. They also tend to be higher for the smaller rudder angle failure at the 1-knot level. An opposite trend occurs when the speed has been reduced to the 0.25-knot level, where the transfer is consistently higher with the larger rudder failure angle, and more so at the higher ship speed. Also, whereas the tug angles required to maintain course are moderate at the 3-knot initial ship speed, the tug angle tends to be saturated at 60° when initial ship speed is 6 knots.

The final headings in the majority of the runs are very close to the initial heading of 270° (except for the 165K DWT tanker with with 35° rudder failure and 6-knot speed). At the point where the speed has been reduced to 0.25 knot (where anchoring is possible), the actual ship course is much greater than the desired heading, due to a high value of the drift angle i.e. the lateral drift speed of the ship is high compared to the forward speed.

The highest transfers (3,698 feet), were registered for the 165K DWT tanker at 6-knot speed and -35° rudder failure angle, followed by the 280K DWT ship (3,439 feet) and then by the 80K DWT ship (1,588 feet). At 3-knot ship speeds, the transfer experienced was minimal for all ships with both rudder failure angles.

Again, rudder-tug angles were always higher when the speed was 6 knots and, in most cases, they saturated at the 60° maximum.

On comparing the results of this rudder-tug retarding/control system to the previous data where only retardation was possible, it is apparent that the system has great potential. This confirms, in a simplified way, the encouraging results that were obtained in the sea trials in Port Valdez in 1978.

5. CORRECTIONS TO VOLUME I OF THE 1978 REPORT

On page 2-23 of the 1978 report, an incorrect set of equations for surge, sway, and yaw was presented, which also included some typographical errors and some omissions. These are corrected below.

The equations shown in Volume I were of the "Eda" form employed in the CAORF simulator whereas those actually used in the computations were a condensed, 3 degrees of freedom, version of the 6 degree of freedom equations appearing in "Ship Dynamics Data Base, 5, Final Report" by C. F. Kottler, (NMRC-KP-157, March 1976) prepared for NMRC. These equations differ essentially only in the form of the rudder forces and moments, and in the values to be assigned to some of the hydrodynamic coefficients.

TABLE 10. RUDDER TUG IN RETARDING MODE (TUG FORCE = 80,000 LB) (TUG ANGLE LIMITED TO -60°)

Rudder Angle Failure	Time to Slow to 1 Knot	Values at 1 knot: Transfer (ft)	Values at 1 knot: Advance (ft)	Values at 1 knot: Heading	Values at 1 knot: Course	Time to Slow to 0.25 knot	Values at 0.25 knot: Transfer (ft)	Values at 0.25 knot: Advance (ft)	Values at 0.25 knot: Heading	Values at 0.25 knot: Course	Max. Advance	Max. Transfer	Max. Tug Angle (deg)
Heading = 270°, Wind = $0/0^{\circ}$, Current = $0/0^{\circ}$													
Ship Type = 80K DWT													
Speed = 3 knots													
-15	5:30	25	1,225	271.93	271.91	7:00	28	1,319	271.49	270.78	1,319'	28'	-12.42
-35	5:30	101	1,216	273.42	278.71	7:00	118	1,319	270.71	288.97	1,319'	118'	-40.68
Speed = 6 knots													
-15	10:00	372	3,701	262.34	270.84	11:30	379	3,819	261.09	282.21	3,819'	379'	-47.89
-35	10:30	1,464	3,024	275.09	307.48	12:30	1,588	3,144	261.09	333.62	3,144'	1,588'	-60.00
Ship Type = 165K DWT													
Speed = 3 knots													
-15	9:30	49	2,160	271.33	272.19	13:30	59	2,320	270.06	274.14	2,320'	59'	-10.98
-35	10:00	178	2,123	270.87	277.01	13:30	211	2,338	266.62	291.79	2,338'	211'	-33.81
Speed = 6 knots													
-15	20:30	730	7,065	263.84	261.60	24:00	702	7,268	267.43	258.41	7,268'	912	-60.00
-35	19:00	3,431	4,136	303.50	332.60	22:30	3,698	4,251	285.20	348.50	4,251'	3,698'	-60.00

TABLE 10. RUDDER TUG IN RETARDING MODE (TUG FORCE = 80,000 LB) (TUG ANGLE LIMITED TO -60°) (CONT)

Rudder Angle Failure	Time to Attain 1 Knot	Values at 1 knot: Trans-fer (ft)	Values at 1 knot: Ad-vance (ft)	Values at 1 knot: Heading	Values at 1 knot: Course	Time to Attain 0.25 knot	Values at 0.25 knot: Trans-fer (ft)	Values at 0.25 knot: Ad-vance (ft)	Values at 0.25 knot: Heading	Values at 0.25 knot: Course	Max. Ad-vance*	Max. Trans-fer*	Max. Tug Angle (deg)
Ship Type = 280K DWT													
Speed = 3 knots													
-15	15:30	106	3,255	270.44	271.05	21:00	109	3,512	269.81	270.98	3,512'	109'	-14.17
-35	14:30	189	2,960	271.48	272.52	20:30	202	3,342	269.98	271.87	3,342'	202'	-27.49
Speed = 6 knots													
-15	30:30	897	10,101	268.80	268.64	36:30	888	9,494	269.29	268.57	9,494'	888'	-60.00
-35	29:30	3,410	8,367	258.76	262.51	35:30	3,361	8,741	260.07	267.19	8,741'	3,439	-60.00

* Values of advance and transfer shown primed are those obtained at speed of 0.25 knot which was when run was terminated.

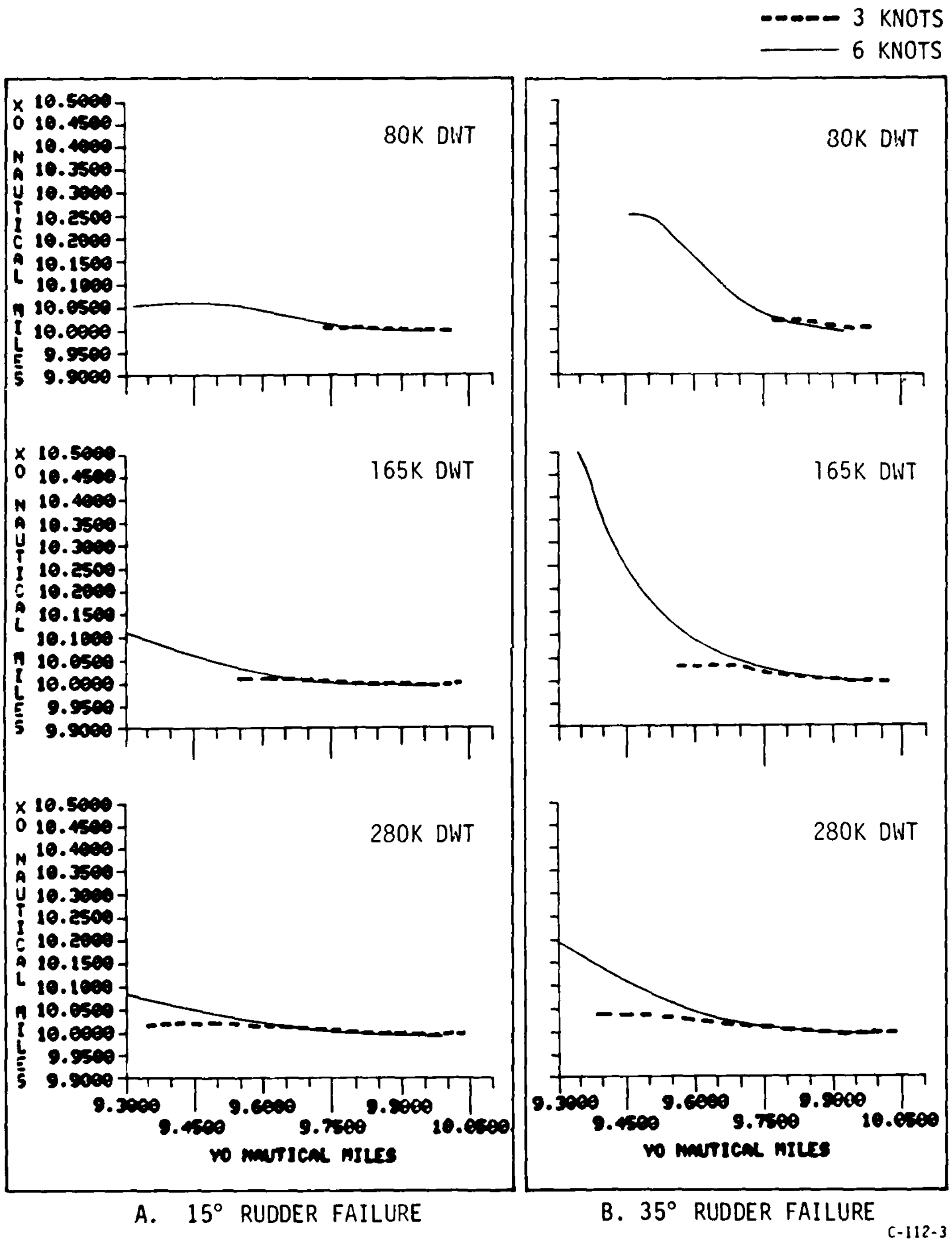


Figure 3. Effectiveness of 80,000 Pound Retarding Tug on 80K, 165K, and 280K DWT Tankers with 15° and 35° Rudder Failure

These 6 DOF equations, when heave, pitch and roll and their coupling with yaw, surge and sway are assumed negligible, reduce to:

$$M(\dot{u} - rv) = 1/2\,\rho\Big[c_o L^2U^2 + c_1 vrL^3 + c_2 L^2 v^2 + c_4 L^3 \dot{u}$$

$$+ K_R L^2U^2 c_3 (\delta + \beta)^2 \cos\beta + K_R L^2 U^2 c_{10} (\delta + \beta) \sin\beta\Big]$$

$$+ (c_{11} u^2 + c_{12}\, un + c_{13}\, n^2) + X_{WIND} + X_{EXT}$$

$$M(\dot{v} + ru) = 1/2\,\rho\Big[b_o L^2U^2 + b_1 L^2 Uv + b_2 rL^3U + b_3 L^2U^2K_R (\delta + \beta)\cos\beta$$

$$+ b_5 \frac{L^3}{U} v^2 r + b_6 \frac{L^4}{U} vr^2 + b_7 \frac{L^2}{U} v^3$$

$$+ b_8 \frac{L^5}{U} r^3 + L^2U^2K_R\, b_9 (\delta^3) + L^2U^2K_R\, b_{10} (\delta + \beta)^2 \sin\beta$$

$$+ b_{12} L^3 \dot{v}\Big] + Y_{WIND} + Y_{EXT}$$

$$I_z \dot{r} = 1/2\,\rho\Big[a_o L^3U^2 + a_1 L^3 Uv + a_2 UL^4 r + a_3 K_R L^3 U^2 (\delta + \beta)\cos\beta$$

$$+ a_5 \frac{L^4}{U} v^2 r + a_6 \frac{L^5}{U} vr^2 + a_7 \frac{L^3}{U} v^3 + a_8 \frac{L^6}{U} r^3$$

$$+ a_9 L^3U^2K_R \delta^3 + L^3U^2K_R\, a_{10} (\delta + \beta)^2 \sin\beta$$

$$+ a_{11} L^5 \dot{r}\Big] + N_{WIND} + N_{EXT}$$

The corrected forms of the "Eda" equations appearing on page 2-23 of Vol. I of the 1978 report are:

$$M(\dot{u} - rv) = 1/2\rho\left[c_oL^2U^2 + c_1vrL^3 + c_2L^2v^2 + c_3K_RL^2U^2\delta^2\right.$$

$$\left. + C_4L^3\dot{u}\right] + \left[c_{11}u^2 + c_{12}un + c_{13}n^2\right]$$

$$+ X_{WIND} + Y_{WIND}$$

$$M(\dot{v} + ru) = 1/2\rho\left[b_oL^2U^2 + b_1L^2Uv + b_2rL^3U + b_3K_RL^2U^2\delta\right.$$

$$+ b_5\frac{L^3}{U}v^2r + b_6\frac{L^4}{U}vr^2 + b_7\frac{L^2}{U}v^3 + b_8\frac{L^5}{U}r^3$$

$$\left. + b_{12}L^3\dot{v} + b_9K_RL^2U^2\delta^3\right] + Y_{WIND} + Y_{EXT}$$

$$I_z\dot{r} = 1/2\rho\left[a_oL^3U^2 + a_1L^3Uv + a_2UL^4r + a_3K_RL^3U^2\delta\right.$$

$$+ a_5\frac{L^4}{U}v^2r + a_6\frac{L^5}{U}vr^2 + a_7\frac{L^3}{U}v^3 + a_8\frac{L^6}{U}r^3$$

$$\left. + a_{11}L^5\dot{r} + a_9K_RU^2L^3\delta^3\right] + N_{WIND} + N_{EXT}$$

6. SUMMARY

- o Studies were made to determine the transfer and advance of a 400K DWT tanker under wind and current conditions similar to previous studies performed on four smaller ship sizes at CAORF. These present studies indicated that both the transfers and the advances that result fall within the same ranges reported previously for the smaller ships.

- Computer runs were made to study the advance and transfer of four ship sizes ranging from 120K to 400K DWT moving at 8-knot speed in the absence of current. The wind conditions imposed were identical to previously reported studies. Retarding dynamic tug forces, calculated by means of a formula derived from the previous data, were used. On this basis, it was found that the actual transfers were very close to the maximum permissible values based on this formula, which was incorporated in the U.S. Coast Guard regulations for tanker vessel traffic in Puget Sound. In fact, the permissible value was very conservative in the case of the largest ship.

- The concept of a rudder tug which can provide either pushing or retarding forces in addition to course-keeping control was investigated. The results were very encouraging and tend to confirm the results of actual sea trials performed in Port Valdez in 1978.

7. RECOMMENDATIONS FOR FURTHER STUDY

The rudder tug concept employed in this study was very basic, and did not attempt to investigate the intricate hydrodynamic problems that are actually present. The study indicates that such investigations should be pursued in the future, so that more realistic comparisons can be made with tanker/tug sea trials. In addition, continued off-line studies that use the "Autotug" concept, followed by interactive off-line studies with a human operator replacing the mathematical model, and eventually on-line studies on the CAORF simulator, should be pursued.

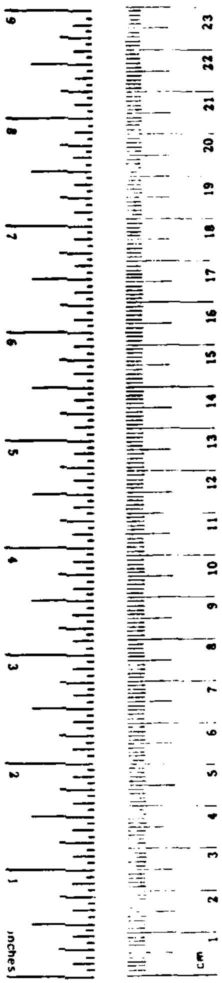
On the basis of the knowledge gained from these endeavors, recommendations can be made to ensure the ultimate safety of tanker operations in confined waterways.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

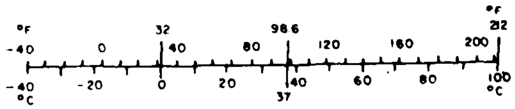
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

[illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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